J Arid Land (2023) 15(11): 1376–1390
https://doi.org/10.1007/s40333-023-0034-3

Science Press Springer-Verlag

Subsurface irrigation with ceramic emitters improves wolfberry yield and economic benefits on the Tibetan Plateau, China

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Abstract: Climate warming has led to the expansion of arable land at high altitudes, but it has also increased the demand for water use efficiency (WUE). To address this issue, the development of water-saving irrigation technology has become crucial in improving water productivity and economic returns. This study aimed to assess the impacts of three irrigation methods on water productivity and economic returns in wolfberry (*Lycium barbarum* L.) cultivation on the Tibetan Plateau, China during a two-year field trial. Results showed that subsurface irrigation with ceramic emitters (SICE) outperformed surface drip irrigation (DI) and subsurface drip irrigation (SDI) in terms of wolfberry yield. Over the two-year period, the average yield with SICE increased by 8.0% and 2.3% compared with DI and SDI, respectively. This improvement can be attributed to the stable soil moisture and higher temperature accumulation achieved with SICE. Furthermore, SICE exhibited higher WUE, with 14.6% and 4.5% increases compared with DI and SDI, respectively. In addition to the agronomic benefits, SICE also proved advantageous in terms of economic returns. Total average annual input costs of SICE were lower than the other two methods starting from the 8th year. Moreover, the benefit-cost ratio of SICE surpassed the other methods in the 4th year and continued to widen the gap with subsequent year. These findings highlight SICE as an economically viable water-saving irrigation strategy for wolfberry cultivation on the Tibetan Plateau. Thus, this research not only provides an effective water-saving irrigation strategy for wolfberry cultivation but also offers insights into addressing irrigation-related energy challenges in other crop production systems.

Keywords: irrigation system; soil water content; soil temperature; water use efficiency; economic benefit

Citation: HAN Mengxue, ZHANG Lin, LIU Xiaoqiang. 2023. Subsurface irrigation with ceramic emitters improves wolfberry yield and economic benefits on the Tibetan Plateau, China. Journal of Arid Land, 15(11): 1376–1390. https://doi.org/10.1007/s40333-023-0034-3

1 Introduction

In recent years, temperature is increasing with the global warming in high-altitude areas, which met the heat demand of crops. Therefore, more and more lands in high-altitude areas were reclaimed (Zhang et al., 2013; Yang et al., 2019). The Tibetan Plateau, being the highest plateau in the world, with arable land increased from 956 km^2 in 1990 to 2180 km^2 in 2020 (Xu et al., 2009; Liu et al., 2021a). The increase in agricultural land area means that more irrigation water is needed to meet the needs of agricultural production. However, due to the impact of climate

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Received 2023-06-20; revised 2023-10-10; accepted 2023-10-27
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change, the water resources of the Tibetan Plateau are decreasing annually (Li et al., 2022). The increase in demand for water resources and the decrease in water reserves not only limit local agricultural production, but also threaten water security in downstream areas (Blaikie and Muldavin, 2004; Barnett et al., 2005). Improving the efficiency of local agricultural water resource utilization is an important measure to alleviate the imbalance between water supply and demand.

Application of water-saving irrigation techniques contributed to an enhancement in WUE (Provenzano et al., 2014). Two widely used irrigation techniques in China are deficit regulation irrigation and alternate root zone irrigation (Kang and Cai, 2002). By regulating water allocation, these techniques reduced crop water consumption without causing a noticeable decline in yield, and increased WUE more than 25% and 41% for deficit regulation irrigation and alternate root zone irrigation, respectively, compared with adequate irrigation (Kang et al., 2017). However, above techniques are frequently combined with drip irrigation and pump systems, which may limit their use in high altitude areas due to high operational energy consumption and difficult energy supply (Tharani and Dahiya, 2018; Powell et al., 2019). In addition, although water-saving irrigation has potential to generate significant ecological and social benefits (Li and Guo, 2014; Liu et al., 2021b), farmers are usually more concerned about its impact on individual economic benefits (Cao et al., 2020). Therefore, cost-effective and low-power ways to increase water productivity should be considered.

A low-pressure subsurface irrigation with ceramic emitters (SICE) technique developed by Wu et al. (2021), which relies on soil water potential differences as irrigation drivers, reduces pressure in the irrigation system, and contributes to lower energy consumption and operating costs. According to experiments and simulations, we found that SICE would be spontaneously and consistently irrigate with "just the right amount", maintaining soil water content within a small range (Cai et al., 2022). And this stable and continuous water supply facilitates improved crop production and simplified field management (Martinez and Reca, 2014; Li et al., 2017). In addition, SICE exhibited significant insulation properties during occasional temperature drops (Cai et al., 2021), which may assist in temperature accumulation of crops to obtain greater yields at high altitude areas. Therefore, this study was conducted on the wolfberry irrigated with SICE technique and the aims are to determine: (1) the validity of SICE, and (2) economic irrigation strategy for wolfberry cultivation on the Tibetan Plateau, China.

2 Materials and methods

2.1 Study area

The experiment was performed in the Hoit Taria Town, Qinghai Province, northeastern Tibetan Plateau, China (37°21′N, 96°44′E; 2869 m a.s.l.). The region has an arid climate, with an annual precipitation of about 200 mm, more than 70% of precipitation falls between June and September, and over 3000 h of sunshine per year with strong evaporation. The weather is very hot in summer and cold in winter, with a frost-free period is approximately 97 d. According to the International Soil Classification System, soil type in this area is loamy sand. The physical properties are shown in Table 1. The reproductive period division of wolfberry and meteorological data in 2018 and 2019 are shown in Table 2.

Table 1 Soil particle composition of the study area

Soil depth (cm)	Clay (%)	Silt (%)	Sand (%)	Bulk density (g/cm^3)	Porosity (%)	Field capacity (cm^3/cm^3)
0–20	0.24	15.62	84.14	1.60±0.08	39.64±1.71	0.16±0.01
20–40	0.44	13.97	85.59	1.71±0.07	35.57±2.02	0.18±0.01
40–60	0.57	18.41	81.02	1.50±0.05	43.24±1.49	0.18±0.01
60–80	0.94	28.69	70.37	1.55±0.04	41.39±1.62	0.19±0.02
80–100	0.71	21.47	77.82	1.55±0.06	41.65±1.56	0.21±0.01

Note: Mean±SD; n=3.

Table 2 Growth period division of wolfberry in 2018 and 2019

Growth period	Date	2018		2019	
		Accumulated precipitation (mm)	Average daily temperature (°C)	Accumulated precipitation (mm)	Average daily temperature (°C)
Germination stage	6 May–10 Jun	25.6	12.9	25.2	12.0
Vegetative stage	11 Jun–14 Jul	29.2	17.4	37.2	16.0
Full-bloom stage	15 Jul–4 Aug	0.0	19.9	0.0	17.8
Summer harvest stage	5 Aug–1 Sep	21.2	17.4	25.6	18.4
Autumn harvest stage	2 Sep–22 Sep	6.4	13.2	0.0	13.0
Whole growth period	6 May–22 Sep	82.4	16.0	88.0	15.6

2.2 Experimental design

The experiment was conducted in a plantation from 2018 to 2019, with 3–4 a old wolfberry trees planted at 0.8 and 1.2 m spacing. Three types of irrigation were used, i.e., surface drip irrigation (DI), subsurface drip irrigation (SDI), and subsurface irrigation with ceramic emitters (SICE; Fig. 1a). DI was supplied by a traditional pump system, adopted the Netafim patch type with sprinkler flow and spacing of 1.10 L/h and 30 cm, respectively. And its irrigation schedule used the experience of local plantations over many years, which was irrigated when soil moisture reached 60% of field capacity, with an irrigation amount of 182 mm throughout the entire growth period. The same schedule was implemented for SDI. SICE used a special water supply system (Fig. 1b and c), which was divided into two parts: a storage tank (80 L) and a supply tank (30 L). The storage tank was used to meet water requirements for continuous irrigation and the supply tank (equipped with floating ball valve inside) was used to maintain constant pressure in the irrigation pipe. A scale was marked on the water storage tank to record water consumption. Meanwhile, to avoid blockages caused by long period and continuous irrigation, we fitted SICE pipes with venting valves at the end, with manual flushing before and after irrigation. To ensure consistent irrigation volume under different irrigation methods, we set irrigation spacing and flow rate to be 20 cm and 0.30 L/h, respectively for SICE treatment. Moreover, depending on soil type and root system distribution of wolfberry (Wang et al., 2020), we installed the subsurface pipes of SDI and SICE at a depth of 30 cm (Fig. 1b). Each treatment uses a pipeline to irrigate 50 trees and repeats three times. All treatments were subjected to similar agronomic methods (such as mulching, trimming, and weeding).

Fig. 1 Subsurface irrigation with ceramic emitters (SICE) irrigation system (a), and layout of subsurface irrigation (b) with ceramic emitters (c).

2.3 Soil and plant measurements

2.3.1 Soil water content (SWC) and evapotranspiration (ET)

SWC and soil temperature at depths of 0–100 cm were measured every 15 d throughout the growth period, and added a test when irrigation activity occurred. After evaluation of site-specific calibration equations by oven drying method, SWC and temperature of 0–20, 20–40, 40–60, 60–80, and 80–100 cm soil depths were measured using a time-domain reflectometry downhole sensor (TRIME-PICO-IPH, IMKO, Ellingen, Germany). Due to more than 75% of wolfberry fine roots are distributed within 0–60 cm of soil (Wang et al., 2020), SWC would be discussed in 0–60 and 60–100 cm soil depths.

The following formula was used to calculate soil water storage (SWS, mm):

$$\mathrm{SWS} = \mathrm{SWC} \times \mathrm{SD}\,, \tag{1}$$

where SWC is the soil water content (%); and SD is the thickness of soil depth (mm).

A soil water balance equation was used to calculate evapotranspiration (ET):

$$\mathrm{ET} = I + P + U - \Delta\mathrm{SWS} - D\,, \tag{2}$$

where ET is the crop evapotranspiration during wolfberry growth period (mm); I is the irrigation amount (mm); P is the effective rainfall (>5 mm) measured by an automatic weather station (mm) (Xie et al., 2018); U is the water movement from deep soil into root zone, which was assumed to be zero in this study as the groundwater table was deeper than 50 m (mm); D is the deep percolation, which is calculated by subtracting soil water content above field capacity from total amount of soil water in root zone (mm); and ΔSWS is the change in soil water content from the beginning to the end of reproductive period in the 0–100 cm soil layer (%).

2.3.2 Growth parameters

Plant height, ground diameter, and leaf area index (LAI) were measured at 15–20 d intervals throughout the growth period of wolfberry. Plant height was measured from the highest point of the main stem to ground with a tapeline; ground diameter was measured with a vernier caliper at 10 cm of main stem from soil surface; and LAI was measured by the LAI-2200C plant canopy analyzer (LI-COR Inc., Lincoln, Nebraska, USA). Meanwhile, LAI and ET were allowed to estimate the inter-plant evapotranspiration (Tuo et al., 2022).

$$E_{\mathrm{s}} = \left(1.21 - 0.70 \times \mathrm{LAI}^{0.5}\right) \times \mathrm{ET}\,, \tag{3}$$

where E_{s} is the inter-plant evaporation (mm); and LAI is the leaf area index.

2.3.3 Yield (Y) and water use efficiency (WUE)

At harvest stage, twelve plants were randomly selected in each treatment to determine dried fruit yield. WUE was calculated as:

$$\mathrm{WUE} = Y / \mathrm{ET}\,, \tag{4}$$

where WUE is the water use efficiency (kg/(hm^2·mm)); and Y is the dried fruit yield (kg/hm^2) (Mo et al., 2016).

2.4 Economic benefit

Economic benefit is a comprehensive indicator of economic activity, which can be expressed in terms of irrigation water productivity (IWP) and benefit cost ratio (BCR) (Hafeez et al., 2014). In addition, we have not calculated all of economic inputs (such as the cost of planting trees, pesticides, etc.) in this trial, and focused on the relationship between irrigation system inputs and benefits.

$$\mathrm{IWP} = C_{\mathrm{s}} \times \frac{Y}{I}\,, \tag{5}$$

$$\mathrm{BCR} = \frac{\sum_{t=1}^{n} C_{\mathrm{s}} \times Y \times (1+r)^{-r}}{\sum_{t=1}^{n} C_{\mathrm{t}} \times (1+r)^{-r}}\,, \tag{6}$$

where IWP is the irrigation water productivity that indicated by gross return divided by irrigation

water supplied to wolfberry (CNY/m^3); C_s is the selling price of wolfberry (CNY/kg); BCR is the benefit cost ratio, which attempts to determine the relationship between benefits and costs of growing wolfberries in irrigation systems. when BCR>1, economic benefit reaches acceptable levels; C_t is the annual total cost (CNY); r is the social discount rate; t is the variable of year; and n is the total number of years to be included in the cumulation.

A costing method for micro-irrigation systems was devised by Wang et al. (2015). The total costs are calculated as sum of capital costs, operating costs, and water costs.

$$C_{\mathrm{t}} = C_{\mathrm{annual}} + C_{\mathrm{operating}} + C_{\mathrm{water}}, \tag{7}$$

where C_{annual} is the annual capital cost (CNY); $C_{\mathrm{operating}}$ is the operating cost (CNY); and C_{water} is the water cost (CNY).

Considering interest rate i, capital recovery factor (CRF), and irrigated area, total capital cost can be converted to annual capital cost (Keller and Bliesner, 1990).

$$\mathrm{CRF} = \frac{i(1+i)^t}{(1+i)^t - 1}, \tag{8}$$

$$C_{\mathrm{annual}} = \mathrm{CRF} \times C_{\mathrm{i}}, \tag{9}$$

where i is the interest rate; and C_{i} is the total capital cost (CNY). Total capital cost is determined by costs of pipes (C_{p}), emitters (C_{e}), pump system (C_{pu}), and ditch (C_{d}).

$$C_{\mathrm{i}} = C_{\mathrm{p}} + C_{\mathrm{e}} + C_{\mathrm{pu}} + C_{\mathrm{d}}. \tag{10}$$

Pipe cost is defined as:

$$C_{\mathrm{p}} = V \times \rho_{\mathrm{m}} \times C, \tag{11}$$

where V is the pipe material volume (m^3); ρ_{m} is the density of pipe material (kg/m^3); and C is the cost per unit weight (CNY/kg). V is calculated by Equation 12.

$$V=10^{-6}\times\pi\times e\times(D+e)\times L, \tag{12}$$

where e is the pipe wall thickness (mm); D is the pipe internal diameter (mm); and L is the pipe length (m).

The required e is defined as:

$$e = \frac{r_{\mathrm{w}} \times H_{\mathrm{a}} \times D}{2\sigma}, \tag{13}$$

where σ is the allowable pipe stress (kPa); r_{w} is the weight of water per unit volume (N/m^3); and H_{a} is the allowable pipe pressure (m).

Emitter cost is defined as:

$$C_{\mathrm{e}} = \frac{A}{S_{\mathrm{e}} \times S_{\mathrm{r}}} \times C_{\mathrm{ei}}, \tag{14}$$

where A is the irrigated area (hm^2); S_{e} and S_{r} are the plant spacing and row spacing of wolfberry (m), respectively; and C_{ei} is the emitter unit price (CNY).

Drip irrigation costs from C_{pu} account for around 9% of total capital cost and this can be approximated as 10% of pipe cost (Dandy and Hassanli, 1996; Wang et al., 2015). As SICE pump system is simple, which approximated at 1% of pipe cost. C_{d} can be considered as the ditching cost of subsurface irrigated farmland.

The annual $C_{\mathrm{operating}}$ was calculated as:

$$C_{\mathrm{operating}} = P_{\mathrm{m}} \times O_{\mathrm{t}} \times C_{\mathrm{energy}}, \tag{15}$$

where P_{m} is the electric motor power required (kW); O_{t} is the irrigation system annual operating time (h); and C_{energy} is the energy unit price (CNY/(kW•h)).

Gross irrigation water per year was determined by actual water applied. It will be equal to I and the water cost (C_{water}) was calculated as:

$$C_{\mathrm{water}} = I \times P_{\mathrm{water}}, \tag{16}$$

where P_{water} is the cost of obtaining water from the source (CNY/m^3), which depends on water

availability and the initial water energy.

2.5 Statistical analysis

The effects of different irrigation methods on soil moisture, soil temperature, crop growth, and yield were assessed by one-way analysis of variance (ANOVA) followed by least significant difference (LSD) test, with P<0.05 level considered statistically significant. All statistical analyses were performed using SPSS Statistics v.18.0 (IBM Corporation, Armonk, NY, USA). Figures were drawn using the Origin 2016 software (Origin Lab, Northampton, MA, USA).

3 Results

3.1 Soil water content

Dynamics of mean SWC over time in different soil layers are shown in Figure 2. In 0–60 cm soil depth, SWC of DI and SDI showed alternating wet and dry status throughout reproductive period, with SWC rising rapidly from 10.8% to 16.2% during irrigation, which equated to 60%–90% field capacity (FC), then gradually declining to pre-irrigation state, and repeated several times. Mean coefficient of variation (CV) in 2018 and 2019 for DI and SDI was 20.3% and 17.5%, respectively. While SWC for SICE remained at 10.4%–14.8% (57.9%–82.0% FC) due to differences in irrigation regimes, and CV was 8.9%, which remained stable compared with DI and SDI. In 60–100 cm soil depth, SWC of DI and SDI fluctuated between 8.2%–12.6% and 8.9%–13.1%, with mean values greater than 10.0%. While SICE remained at 8.8%–10.7% and stayed close to the initial state. In addition, because there was very little rainfall in the area and minor variations in climate between the two test periods, the alterations in SWC were similar for the same treatment in both test periods.

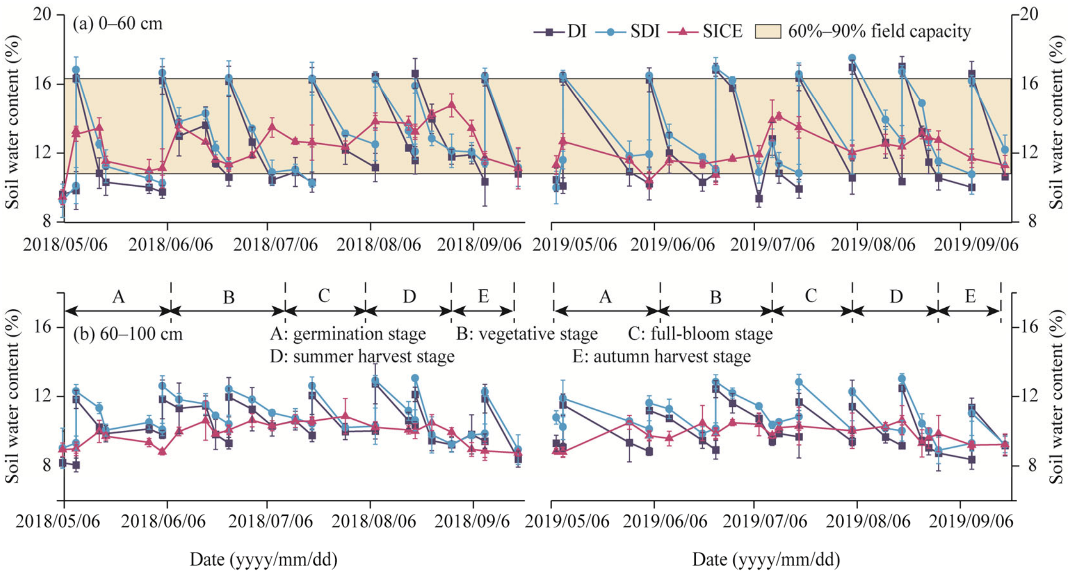

Fig. 2 Variations of soil water content in depths of 0–60 (a) and 60–100 cm (b) over different growth stages. DI, surface drip irrigation; SDI, subsurface drip irrigation; SICE, subsurface irrigation with ceramic emitters. Bars are standard errors.

3.2 Soil temperature

Average soil temperature variations in 0–60 cm soil depth at different stages in 2018 are shown in Figure 3. There was a lag between soil and atmospheric temperatures at daily scales, with soil temperatures starting to rise after 12:00 (LST) and atmospheric temperatures often before 10:00. Meanwhile, soil temperature variation range (R) was obviously smaller than air temperature because the specific heat capacity of soil was greater than that of air, and DI (R=3.8) was

significantly higher than SDI (R=2.0) and SICE (R=0.8) as influenced by soil moisture. Additionally, the difference in daily cumulative temperature among the three treatments decreased as temperature rose. At full-bloom stage, temperature of DI was only about 0.2°C and 0.8°C less than those of SDI and SICE. From whole growth period, average daily temperature of SICE increased by 1.3°C and 0.9°C compared with DI and SDI, with growth rates of 7.1% and 5.2%, respectively.

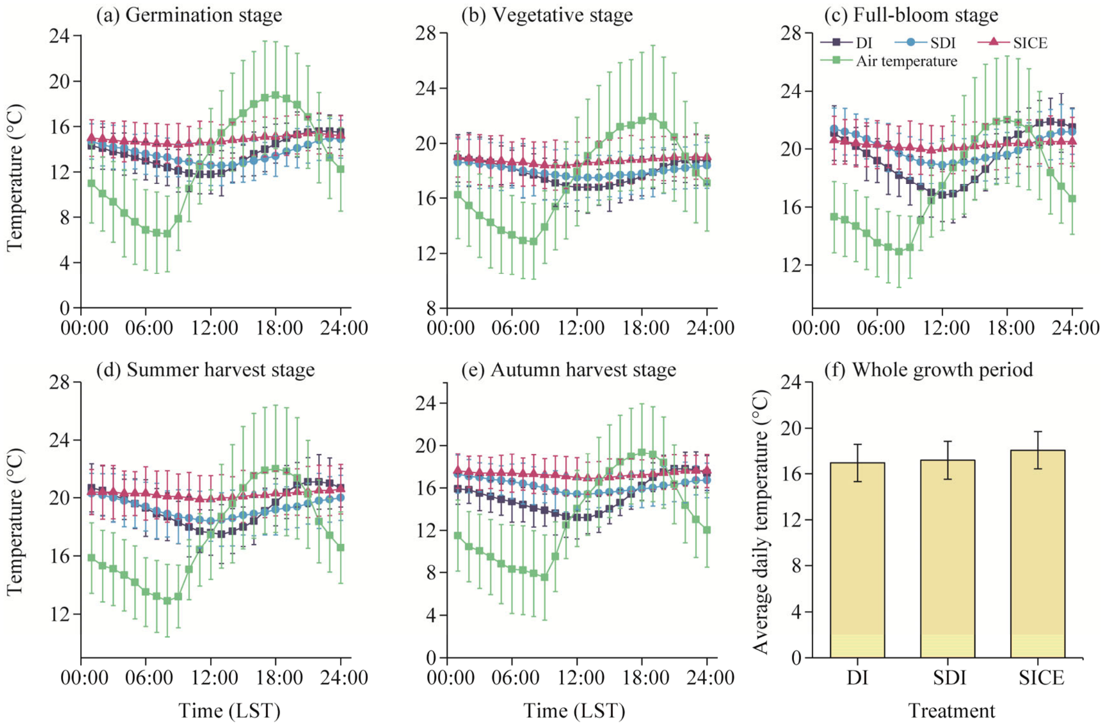

Fig. 3 Soil temperature variations in 0–60 cm soil depth at different growth stages in 2018. (a), germination stage; (b), vegetative stage; (c), full-bloom stage; (d), summer harvest stage; (c), autumn harvest stage; (f), whole growth period. DI, surface drip irrigation; SDI, subsurface drip irrigation; SICE, subsurface irrigation with ceramic emitters; LST, local standard time. Bars are standard errors.

3.3 ET and soil evaporation

Average daily ET and soil evaporation for each treatment at different stages in 2018 and 2019 are shown in Figure 4. DI and SDI had same ET variation pattern at different stages, decreased from germination stage to full-bloom stage (from 2.1 to 1.2 mm), with a large increase at summer harvest stage and then continued to decrease (from 2.6 to 1.3 mm). Whereas ET of SICE increased continuously from germination stage to summer harvest stage (about from 1.4 to 2.7 mm), and then began to decline. Notably, ET of SICE was significantly lower than those of DI and SDI at germination stage due to irrigation regime, with the decreases of 32.8% and 29.7% in 2018 and 2019, respectively. However, due to the differences in crop growth, SICE increased by 44.6% and 53.0% compared with DI and SDI, at full-bloom stage. Meanwhile, the highest ET values of DI, SDI, and SICE all occurred at summer harvest stage, and accounted for 28.3%, 28.2%, and 30.8% of the total ET, respectively. Moreover, soil evaporation changes among the three treatments were generally consistent, showing a decrease trend at summer harvest stage, soil evaporation values of DI and SDI were larger at germination stage and summer harvest stage, accounting for 12.8% and 12.2% of the total ET for DI, and 12.4% and 11.3% for SDI, respectively. SICE only had a large soil evaporation at summer harvest stage and accounted for 11.7% of the total ET.

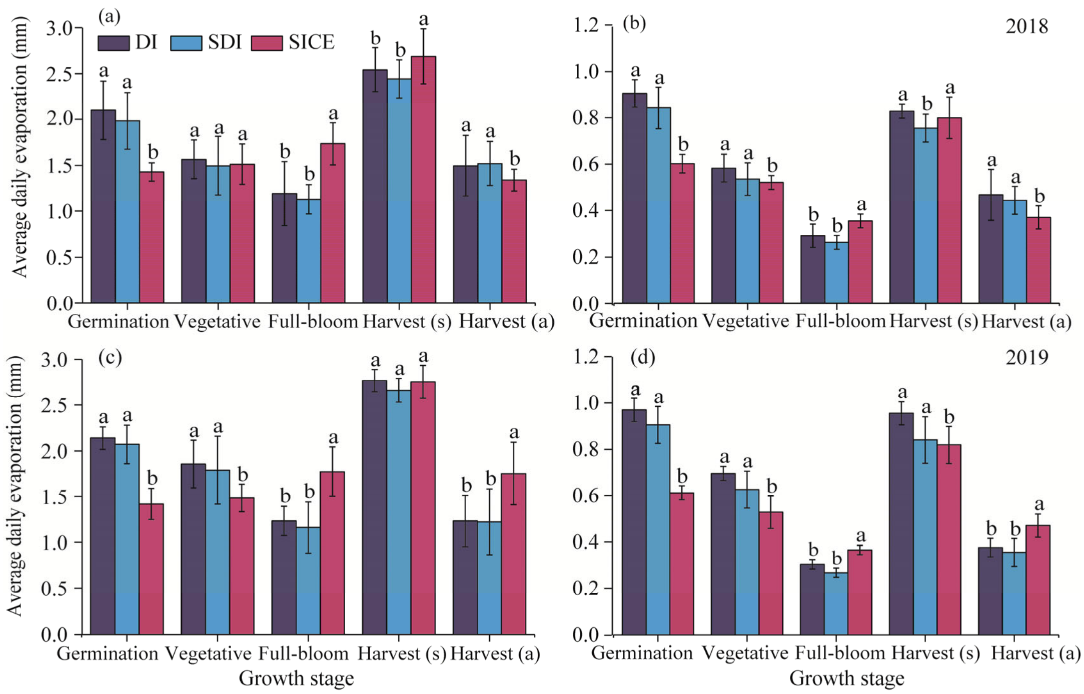

Fig. 4 Average daily evapotranspiration (ET, a and b) and soil evaporation (c and d) for each treatment at different stages in 2018 and 2019. Different lowercase letters within the same stage indicate significant differences among different treatments at $P<0.05$ level. Harvest (s), summer harvest stage; Harvest (a), autumn harvest stage; DI, surface drip irrigation; SDI, subsurface drip irrigation; SICE, subsurface irrigation with ceramic emitters. Bars are standard errors.

3.4 Growth parameters, yield, and WUE

Variations of plant height, ground diameter, and LAI for wolfberry in 2018 and 2019 are shown in Figure 5. Plant height and ground diameter increased as wolfberry grew, while LAI peaked at the summer harvest stage and then gradually decreased. Among the treatments of DI, SDI, and SICE, plant height was affected by pruning, and there were only significant differences at the end of reproduction. While the differences in ground diameter and LAI were obvious, a slight decrease in growth parameters at full-bloom stage was found for DI and SDI. During the two years experiment, the highest plant growth was found for SICE. Average ground diameter of DI increased by 2.84 mm, and they were 3.01 and 3.24 mm for SDI and SICE, respectively. Average LAI peaked at 1.37 for DI, and they were 1.46 and 1.52 for SDI and SICE, respectively.

Yield and WUE followed a similar pattern to wolfberry growth between treatments (Table 3), average yield and WUE of DI were 2788.1 kg/hm^2 and 10.6 kg/(hm^2·mm), 2944.0 kg/hm^2 and 11.7 kg/ (hm^2·mm) for SDI, 3012.5 kg/hm^2 and 12.2 kg/(hm^2·mm) for SICE, respectively. Yield of SICE increased by 8.0% and 2.3%, and WUE increased by 14.6% and 4.5% compared with those of DI and SDI.

3.5 Economic benefit

Table 4 and 5 show the input data and pipeline characteristics required to calculate local capital costs. Economic revenues and expenditures for DI, SDI, and SICE were calculated from the above data as shown in Table 6. The costs and economic benefits over 10 years were estimated in Figure 6.

Among input costing, SICE emitters cost approximately 2.8 times more than DI and SDI, increased 3819.6 CNY/hm^2, but construction costs for the pump system reduced 1262.8 CNY. Meanwhile, taking into account the depreciation and operation of irrigation system, total annual cost of SICE was less than SDI from the 3rd year onwards and less than DI from the 8th year

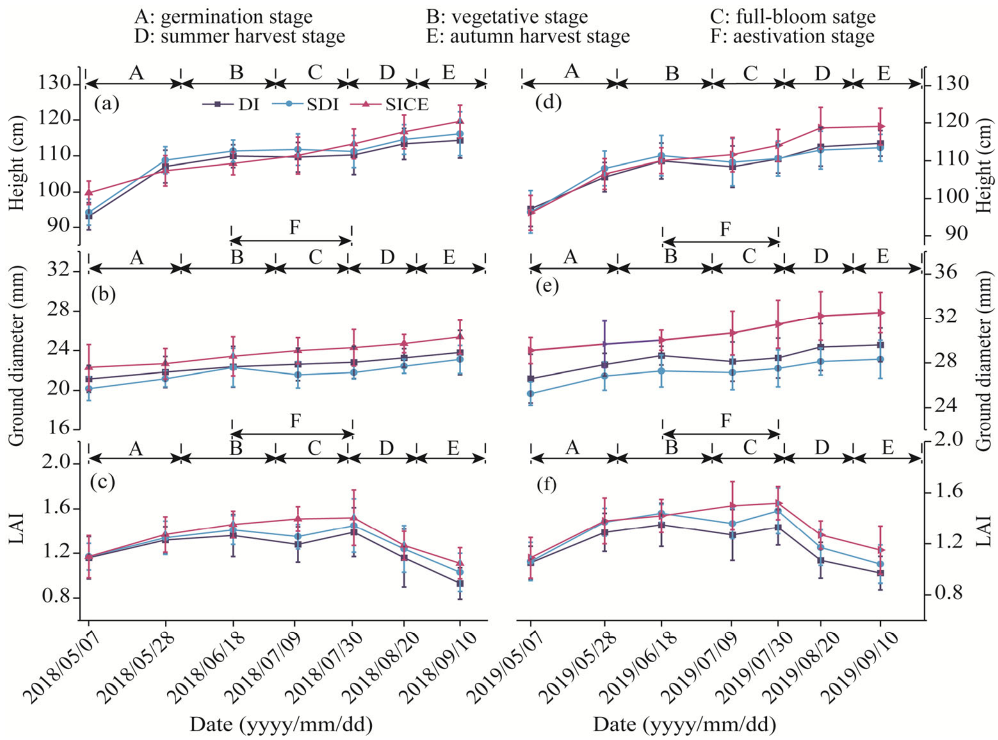

Fig. 5 Growth parameters of wolfberry at different stages in 2018 (a–c) and 2019 (d–f). LAI, leaf area index. DI, surface drip irrigation; SDI, subsurface drip irrigation; SICE, subsurface irrigation with ceramic emitters. Bars are standard errors.

Table 3 Yield and WUE of wolfberry for each treatment in 2018 and 2019

Year	Treatment	ET (mm)	Yield (kg/(hm^2•a))	WUE (kg/(hm^2•mm))
2018	DI	256.4^a	2931.5^c	11.4^c
	SDI	246.2^b	3126.4^b	12.7^b
	SICE	242.6^b	3199.6^a	13.2^a
2019	DI	269.4^a	2644.8^c	9.8^c
	SDI	259.9^b	2761.5^b	10.6^b
	SICE	252.7^b	2844.4^a	11.3^a

Note: WUE, water use efficiency; ET, evaporation; DI, surface drip irrigation; SDI, subsurface drip irrigation; SICE, subsurface irrigation with ceramic emitters. Different lowercase letters within the same year indicate significant differences at P<0.05 level.

Table 4 Input data for economic calculation

Parameter	Value	Parameter	Value
$S_{e\text{-DI,SDI}}$ (m)	0.3	$C_{ei\text{-DI,SDI}}$ (CNY/unit)	0.05
$S_{e\text{-SICE}}$ (m)	0.8	$C_{ei\text{- SICE}}$ (CNY/unit)	0.50
S_r (m)	1.2	C_s (CNY/kg)	30
P_w (CNY/m^3)	0.15	C_{energy} (CNY/(kW•h))	0.58
P_m (kW)	75	C_d (CNY/hm^2)	1500
O_t (h)	12	r	0.06
I (m^3/hm^2)	1820	i	0.06

Note: $S_{e\text{-DI,SDI}}$ and $S_{e\text{-SICE}}$ are the emitter spacing of DI, SDI, and SICE, respectively; S_r, row spacing of wolfberry; P_w, cost of obtaining water from source; P_m, electric motor power required; O_t, irrigation system annual operating time; I, irrigation amount; $C_{ei\text{-DI,SDI}}$ and $C_{ei\text{-SICE}}$ are the emitter unit price of DI, SDI and SICE, respectively; C_s, selling price of wolfberries; C_{energy}, energy unit price; C_d, selling price of wolfberry; r and i are the social discount rate and interest rate, respectively.

Table 5 Pipeline characteristics for determining capital cost

Item	ρ_m (kg/m^3)	C (CNY/kg)	H_a (m)	σ (kPa)
Lateral	900	18	40	2000
Manifold	1200	30	50	2500

Note: ρ_m, density of pipe material; C, cost per unit weight; H_a, allowable pipe pressure; σ, allowable pipe stress.

onwards. In addition, all three irrigation methods recovered the irrigation investment in the first year when planted with wolfberries. SICE offered considerable economic benefits due to increased yield, which increased IWP by 8.0% and 2.5% compared with DI and SDI. BCR of SICE exceeded that of SDI in the 2nd year and DI in the 4th year. Compared with DI and SDI, BCR of SICE increased to 4.7% and 6.9% in the 5th year, and in the 10th year, it reached 13.5% and 14.9% (Fig. 6).

Table 6 Cost, income, and economic efficiency

Parameter	DI	SDI	SICE
C_p (CNY)	12,928.6	12,928.6	11,682.5
C_e (CNY)	1388.9	1388.9	5208.5
C_{pu} (CNY)	1431.8	1431.8	168.9
C_d (CNY)	0.0	1500.0	1500.0
C_i (CNY)	15,749.3	17,249.3	18,559.9
$C_{operaing}$ (CNY)	522.0	522.0	26.1
C_{water} (CNY)	273.0	273.0	237.0
$C_s \times Y$ (CNY)	83,643.8	88,318.5	90,375.0
Irrigation water productivity	46.0	48.5	49.7

Note: DI, surface drip irrigation; SDI, subsurface drip irrigation; SICE, subsurface irrigation with ceramic emitters; C_p, cost of pipes; C_e, cost of emitters; C_{pu}, cost of pump system; C_d, cost of ditch; C_i, total capital cost; $C_{operaing}$, operating cost of irrigation system. Considering SICE irrigation pressure of 5% of DI and SDI, the operating cost is also estimated at 5%; C_{water}, cost of water; C_s, selling price of wolfberry; Y, dried fruit yield of wolfberry, and estimated as the average yield of a two-year experiment.

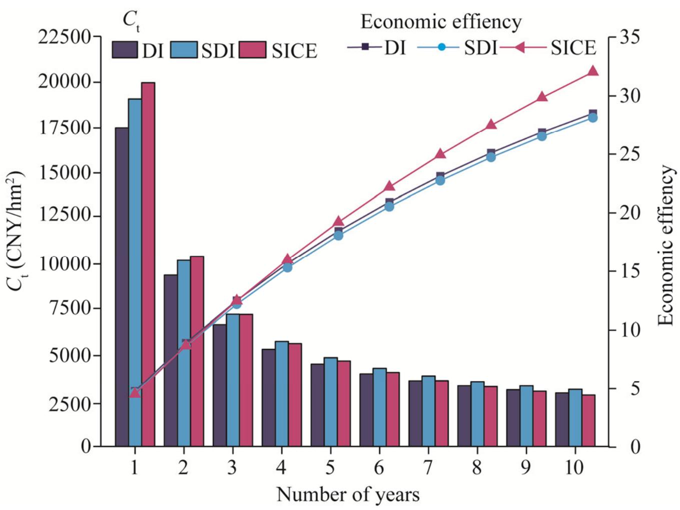

Fig. 6 Estimated cost (C_t) and economic effiency over 10 a. DI, surface drip irrigation; SDI, subsurface drip irrigation; SICE, subsurface irrigation with ceramic emitters.

4 Discussion

4.1 Soil hydrothermal environment

Soil hydrothermal conditions were important factors affecting crop growth in arid areas (Qi et al.,

2016), which were further enhanced at high altitudes due to heavy evaporation and temperature differences (Tesfahunegn and Wortmann, 2008; Guo et al., 2018). Influenced by irrigation schedule, SWC showed a clear alternation between wet and dry in DI and SDI, and small fluctuations in SICE, these trends were generally consistent with other studies (Colak et al., 2017; Cai et al., 2021). DI and SDI had larger CV values in this study, about twice higher than SICE. At the end of irrigation, DI had the maximum horizontal wetting distance and SWC at soil surface, but due to water evaporation and redistribution, soil moisture significantly reduced until next irrigation to refill (Monjezi et al., 2013; Khorsand et al., 2019). SDI had a saturated area in the soil when irrigation finished, which increased SWC in deeper soil although it reduced evaporation loss (Diamantopoulos and Elmaloglou, 2012). Meanwhile, soil water saturation would reduce the oxygen content, which had adverse effects on plant root growth and nutrient uptake (Pendergast et al., 2019). These reasons decreased WUE of DI and SDI. In contrast, stable soil moisture conditions at SICE contributed to crop production (Li et al., 2017), but the stable level of SWC also had to be considered. Adverse effects might also be caused when SWC was stable below or above specific thresholds that triggered severe drought stress or internal flooding (Nam et al., 2020). In this trial, by designed multiple SICE treatments and selected irrigation amounts consistent with DI and SDI, SWC was stable in the range of 10.4%–14.8% (57.9%–82.0% FC) and increased wolfberry yield.

Meanwhile, as an important medium for soil energy exchange, soil water influences the variation and accumulation of soil temperature (Abu-Hamdeh et al., 2001). Given that factors such as soil texture, topography, and temperature that influence soil temperature are consistent under the same experimental conditions, the variation in soil temperature was primarily caused by soil moisture level. During the whole stages, air temperature exerted a dominant influence on changes in soil temperature. Numerous studies have also corroborated that both water recharge and air temperature constitute pivotal factors affecting soil temperature (Jungqvist et al., 2014; Yang et al., 2018). Moreover, SICE provided a greater specific heat capacity by keeping soil moisture for longer time, when soil temperature increased following air temperature, and cumulative temperature differences between SICE and other treatments decreased. Previous study showed that SICE provides better insulation during sudden changes in temperature (Cai et al., 2021). However, since low temperatures are frequently observed at high altitudes (Grimalt et al., 2004), the lower soil temperature at high altitudes led to a reduction in water uptake by crop roots (Ozer et al., 2020). This study evaluated the influence of various irrigation methods on soil temperature over the complete growth period and determined that SICE was capable of sustaining soil temperature, mitigating cold stress, and fostering crop growth (Thomashow, 1999; Ghorbanpour et al., 2018).

4.2 Plant growth and evapotranspiration

Rapid and stable plant growth were important for yield (Li et al., 2016). In the two-year trial, three treatments had similar growth rates, but growth parameters of DI and SDI showed a sudden drop at full-bloom stage. We speculated that it was caused by the imposed dormancy of wolfberry. Imposed dormancy means that growth is forced to be extremely slow or briefly quiescent when plants encounter adverse conditions such as low temperature and drought during reproductive stage (Volaire and Norton, 2006). This phenomenon was mainly manifested by branches withering, leaves falling or main stem shrinking (Wang et al., 2020). Because soil evaporation and plant transpiration rapidly depleted soil water after drip irrigation (Colak et al., 2017), temporary drought conditions occurred between wet and dry periods when employing drip irrigation. At the same time, full-bloom stage was characterized by low rainfall and high temperatures (Table 2), and water requirements were even more intense. Moreover, research indicated that vegetation ecosystem resistance at high altitudes is lower under extreme drought conditions (Chen et al., 2020). These three reasons might have collectively contributed to the unstable growth of wolfberry under DI and SDI. On the contrary, due to continuous water supply and stable soil moisture environment, SICE improved soil drought and inhibited imposed dormancy in wolfberry,

resulting in a higher growth parameter.

ET is an important basis for determining water management practices, designing irrigation systems and regimes (Allen et al., 1998; Kool et al., 2014). Understanding ET patterns during crop growth plays a crucial role in assessing irrigation practices. The most striking feature of this trial was that DI and SDI showed a decreasing trend in ET from germination stage to full-bloom stage, which appeared opposite to crop growth, while SICE showed a consistent trend in ET and crop growth. In general, crop ET should be rising in the early stages of growth (Tuo et al., 2022). This may be explained by the following two reasons. Firstly, irrigation strategies of DI and SDI were influenced by the combination of soil moisture condition and irrigation cycle, with plants being fully irrigated only when soil became fairly dry, and this is common in commercial plant production (Nam et al., 2020). DI and SDI were irrigated twice at the beginning of reproductive stage (germination stage) and only once at other growth stages (Fig. 2). Secondly, precipitation had little effect on the irrigation regime of DI and SDI due to poor soil texture and sparse rainfall. So, as irrigation and rainfall decreased, ET of DI and SDI continued to decrease with wolfberry growth. As SICE adjusted outflow according to soil moisture conditions (Cai et al., 2022), we used reduced emitter output during rainfall in water shortage periods, which was equivalent to extended use of rainfall and increased availability of rainwater. Meanwhile, small and continuous water supply from SICE also contributed to limit water evaporation and discharge, further improving WUE (Martinez and Reca, 2014).

4.3 WUE and economic benefit

Increased WUE and economic benefit are important for improving the ecological environment, developing agricultural production, and raising incomes of farmers at high altitudes (Liu et al., 2013; Cao et al., 2020). In this experiment, SICE treatment had the highest WUE perhaps due to several factors combined. Firstly, low temperatures tended to constrain crop yields at high altitudes (Guo et al., 2018), while the stable soil moisture maintained by SICE promoted more suitable soil temperatures for the growth of high altitude crops. Secondly, water stress generated between alternate wet and dry cycles at the same irrigation amount, resulted in reduced growth and yield of wolfberry (Zhao et al., 2018). While continuous water supply avoided the imposed dormancy and enhanced wolfberry growth and accumulation. Thirdly and most importantly, SICE could autonomously adjust the emitter flow rate based on soil moisture conditions to increase WUE. A variable rate irrigation (VRI) technology also demonstrated that adapting water supply rates to soil and crop characteristics helped conserve water and improved WUE (Omary et al., 1997; Sui and Yan, 2017; Neupane et al., 2021). Depending on combination of crops and weather conditions, VRI could lead to water savings of 10%–15% (Sadler et al., 2005). Although SICE irrigation system does not use sophisticated monitoring equipment such as VRI (Sui et al., 2020), micro-regulation was achieved by reduced emitter outflow rate and continuous irrigation, and its feasibility has been verified in this experiment and other simulations (Cai et al., 2022). However, this trial only considered the same irrigation amount for SDI and SICE as DI, while SDI and SICE still had the potential to improve the water productivity by adjusting irrigation amount. Meanwhile, SICE requires more systematic simulation methods to determine the relationship between irrigation amount and SWC level.

Trying new water-saving irrigation methods requires an assessment of production costs and economic benefits, which will help farmers to choose appropriate management practices (Darouich et al., 2014). In this trial, SICE required higher inputs in the initial construction, but due to low operating costs, the average annual input costs of SICE started to be lower than the other treatments from the 8th year onwards. Meanwhile, BCR of SICE treatment exceeded that of the other treatments from the 4th year onwards due to its relatively high yield. In addition, in sparsely populated high altitude areas, labor is an important potential factor in agricultural production. In Ecuador, farmers have opted to use water-saving irrigation techniques in order to reduce the need for labor (Mo et al., 2017). SICE only needs to design the parameters before irrigation, and operation management under continuous irrigation is simple. Reduced labor costs may further enhance the economic benefits of SICE. However, the cost of ceramic emitters is still

much higher than plastic pipes due to preparation process and material formulation (Zhou et al., 2020). In this trial, the cost of SICE emitters increased by 3819.6 CNY/hm^2 compared with DI and SDI, representing 20.6% of its total capital cost. Thus, cheaper ceramic emitters should be considered to design.

5 Conclusions

A two years field experiment was conducted to assess the performance of DI, SDI, and SICE in wolfberry cultivation on the Tibetan Plateau, China. The results indicated that SICE could provide a relatively stable soil moisture environment and increase the cumulative soil temperature under similar water consumption compared with DI and SDI. On this basis, SICE treatment enhanced the growth and yield of wolfberry by improving hydrothermal environment. Moreover, SICE contributed to higher productivity and WUE in wolfberry cultivation on the Tibet Plateau. Although SICE treatment required higher initial investment, its lower operational costs caused the gradual surpassing of DI and SDI treatments in terms of BCR over time. Therefore, SICE not only maintained economic return but also reduced the energy consumption for irrigation system. In summary, this study verified the technical advantages of SICE, which included low pressure, low flow, and continuous irrigation feature. Unfortunately, the study did not consider the integrated water-fertilizer effects under SICE treatment, hence the future research should pay more attention to the movement, absorption, and transformation of water and fertilizer under SICE treatment.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the National Natural Science Foundation of China (52079131, 51779246). We would like to thank the editors and reviewers for their constructive feedback.

Author contributions

Conceptualization: HAN Mengxue, ZHANG Lin; Data curation: HAN Mengxue; Formal analysis: HAN Mengxue, ZHANG Lin; Funding acquisition: ZHANG Lin; Investigation: HAN Mengxue; Methodology: ZHANG Lin; Project administration: HAN Mengxue; Resources: ZHANG Lin; Supervision: ZHANG Lin, LIU Xiaoqiang; Validation: ZHANG Lin, LIU Xiaoqiang; Visualization: HAN Mengxue, LIU Xiaoqiang; Writing - original draft: HAN Mengxue; Writing - review & editing: HAN Mengxue, ZHANG Lin, LIU Xiaoqiang.

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